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● *Original Contribution*

QUANTIFICATION OF ELASTIC HETEROGENEITY USING CONTOURLET-BASED TEXTURE ANALYSIS IN SHEAR-WAVE ELASTOGRAPHY FOR BREAST TUMOR CLASSIFICATION

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Abstract—Ultrasound shear-wave elastography (SWE) has become a valuable tool for diagnosis of breast tumors. The purpose of this study was to quantify the elastic heterogeneity of breast tumors in SWE by using contourlet-based texture features and evaluating their diagnostic performance for classification of benign and malignant breast tumors, with pathologic results as the gold standard. A total of 161 breast tumors in 125 women who underwent B-mode and SWE ultrasonography before biopsy were included. Five quantitative texture features in SWE images were extracted from the directional subbands after the contourlet transform, including the mean (T_{mean}), maximum (T_{max}), median (T_{med}), third quartile (T_{qt}), and standard deviation (T_{sd}) of the subbands. Diagnostic performance of the texture features and the classic features was compared using the area under the receiver operating characteristic curve (AUC) and the leave-one-out cross validation with Fisher classifier. The feature T_{mean} achieved the highest AUC (0.968) among all features and it yielded a sensitivity of 89.1%, a specificity of 94.3% and an accuracy of 92.5% for differentiation between benign and malignant tumors *via* the leave-one-out cross validation. Compared with the best classic feature, *i.e.*, the maximum elasticity, T_{mean} improved the AUC, sensitivity, specificity and accuracy by 3.5%, 12.7%, 2.8% and 6.2%, respectively. The T_{med}, T_{qt} and T_{sd} were also superior to the classic features in terms of the AUC and accuracy. The results demonstrated that the contourlet-based texture features captured the tumor's elastic heterogeneity and improved diagnostic performance contrasted with the classic features. (E-mail: Zhangq@shu.edu.cn or hr.zheng@siat.ac.cn)

Key Words: **Shear-wave elastography (SWE), Contourlet-based texture analysis, Elastic heterogeneity, Breast tumor, Ultrasound.**

INTRODUCTION

Ultrasonic elastography is a non-invasive imaging modality that depicts tissue stiffness by displaying contrast for, or measuring quantities related to, the shear elastic modulus of tissue (Bamber et al. 2013; Bercoff et al. 2004; Ophir et al. 1991; Sarvazyan et al. 1998). Breast ultrasonic elastography has become a useful tool for diagnosis of breast tumors during the past few y. Improvement of the elastography techniques allows better characterization of breast tumors (Balleyguier et al. 2013; Bamber et al. 2013).

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There are three categories of ultrasonic elastography: the displacement or strain imaging, the shear-wave speed measurement, and the shear-wave speed imaging (Bamber et al. 2013). The displacement or strain imaging includes various commonly used elastography techniques, such as the strain elastography (freehand or assisted-freehand) (Kadour and Noble 2009; Ophir et al. 1991), the acoustic radiation force impulse (ARFI) imaging (Nightingale et al. 2002b; Nightingale et al. 2001) and the strain-rate imaging (Sutherland et al. 1994). These techniques all detect the tissue displacement and display it directly or convert it to the strain for visualization. However, they can only provide a qualitative elasticity image that represents the relative elastic distribution between a breast tumor and its surrounding normal tissue (Xiao et al. 2014), reducing its repeatability. The shear-wave speed measurement, as represented by the transient elastography (Sandrin et al. 2002) and the ARFI Virtual Touch tissue quantification technique (Nightingale et al. 2002a; Palmeri and Nightingale 2011), calculates a regional or beam-line average shear-wave speed quantitatively, but it does not provide a 2-D image, limiting its application on breast tumor characterization. The shear-wave speed imaging, also known as the shear-wave elastography (SWE), uses an acoustic radiation force focused at various depths and thus reconstructs and visualizes the shear-wave speed as a 2-D image, enabling quantitative representation of tissue mechanical properties (Nightingale et al. 2003; Palmeri and Nightingale 2011; Sarvazyan et al. 1998). The SWE has been made commercially available by combining the acoustic radiation force with an ultrafast imaging scanner (Athanasiou et al. 2010; Bercoff et al. 2004), providing 2-D quantitative elasticity images of breast tumors. The SWE is more reproducible than the displacement or strain imaging (Cosgrove et al. 2012). Moreover, it is more practical for clinical use than the shear-wave speed measurement, thanks to its extension of the measurement scale from a single point to a 2-D space (Bamber et al. 2013).

SWE has gained increasing interest for characterization of breast tumors. From SWE images, several quantitative features have been calculated to represent mechanical characteristics of a breast tumor, such as the mean (E_{mean}) and maximum (E_{max}) of Young's modulus and various elasticity ratios (Choi et al. 2014; Xiao et al. 2014). The features with the optimal Youden's indices (the sum of sensitivity and specificity minus one) reported in literatures are enumerated in Table 1. The best Youden's index, classification accuracy and area under the receiver operating characteristic curve (AUC) among all the features were 83.9%, 92.1% and 0.963, respectively. There were still a few false-positive results and false-negative results in these studies, limiting the clinical use of SWE (Yoon et al. 2013a).

Malignant breast tumors are histologically heterogeneous because parts of malignant tumors are more cellular, more likely to have associated lymphocytic infiltrates and/or more likely to have necrosis (Gweon et al. 2013b). Therefore, features representing tumor heterogeneity could aid benign and malignant differentiation (Evans et al. 2010). There are qualitative features proposed to score the extent of elastic heterogeneity of breast tumors by visual observation and manual grading. Tozaki and Fukuma (2011) introduced four color patterns (COLp) to visually examine the elastic heterogeneity: blue homogeneous coding, vertical stripes, a localized colored area at a lesion's margin, and heterogeneously colored areas in a lesion's interior. The classification accuracy with the COLp was between 70.0% and 88.0%, and the AUC ranged from 0.799 to 0.947 (Gweon et al. 2013a; Gweon et al. 2013b; Lee et al. 2013a; Tozaki and Fukuma 2011; Yoon et al. 2013b; Youk et al. 2013b). In a multinational study of 939 breast masses, Berg et al. (2012) used a three-grade feature (E_{homo}) to depict the elasticity of a mass as very homogeneous, reasonably homogeneous, or heterogeneous, and yielded an accuracy of 83.9%. These two qualitative features had both demonstrated that tumors with heterogeneous elasticity were very likely to be malignant. However, the manual examination was subject to observers' experience, leading to high inter- and intra-observer variability. Thus, quantification of the tumor heterogeneity in SWE is required to reduce the variability and augment the diagnostic performance.

Table 1. Features derived from SWE images reported in literatures—for each study, only the features with the optimal Youden's indices, *i.e.,* the sum of sensitivity and specificity minus one, are listed

Literature	Lesion no.	Patient no.	Feature*	Sensitivity (%)	Specificity (%)	Youden's index (%)	Accuracy (%)	AUC†
Youk et al. 2013a	163	146	E_{max}	91.7	92.2	83.9	92.1	0.961
Gweon et al. 2013a	153	152	E_{col}	88.5	92.5	81.0	91.5	0.932
Chang et al. 2013	150	129	E_{mean}	95.8	84.8	80.6	90.0	0.928
Lee et al. 2013b	144	134	E_{mean}	89.5	89.6	79.1	89.6	0.938
Gweon et al. 2013b	133	119	SD	88.9	89.7	78.6	89.5	0.944
Xiao et al. 2014	125	93	*PTErat*	79.5	98.8	78.3	92.0	0.963
Berg et al. 2012	939	939	E_{col}	98.6	78.5	77.1	84.7	0.962
Chang et al. 2011	182	158	E_{mean}	88.8	84.9	73.7	86.8	0.932
Evans et al. 2012	175	173	E_{mean}	95.0	77.0	72.0	89.0	N/A
Youk et al. 2013b	389	324	COLp	94.2	77.7	71.9	82.8	0.859
Tozaki and Fukuma 2011	100	96	COLp	91.3	80.6	71.9	88.0	N/A
Lee et al. 2013a	156	139	E_{max}	88.9	77.5	66.4	80.1	0.860
Yoon et al. 2013b	267	236	E_{max}	81.4	81.7	63.1	81.7	0.843
Wang et al. 2013	114	108	E_{max}	60.9	85.6	46.5	75.4	0.741

* E_{mean}, E_{max} and SD are the mean, maximum and standard deviation of the Young's modulus within a ROI, respectively. *PTErat* denotes the ratio of the mean value in the peri-tumoral area to the mean value outside the peri-tumoral area. E_{col} is a six-point color score of E_{max} based on visual color overlay. COLp represents the qualitative feature prescribing four-color patterns.

† AUC, area under the receiver operating characteristic curve; ROI = region of interest; SWE = shear-wave elastography.